DISCUSSION BEFORE THE MEASUREMENTS AND RADIO SECTIONS, 8TH MARCH, 1949

Mr. W. H. Ward: The Q-meter was introduced about ten years ago and is now one of the commonest instruments in radio laboratories. Until now there have apparently been no major papers on these instruments since the original descriptions, and that is a sufficient measure of the importance of the present paper. It introduces a new instrument that should be a considerable improvment on the existing patterns, and I am glad to see that it has what the authors rightly call the salient features of the Q-meter—direct readings in frequency, capacitance, and Q.

It used to be accepted as good practice to induce into a tuned circuit through the loosest possible coupling, and some of us were rather horrified by the tightness of coupling used in the Boonton instrument. The new one has not this defect; because C_1 is so small the coupling is very loose, a fact which is all to the good so long as there is no leakage past this condenser. The design has clearly been arranged with this in mind, but have the authors any experimental evidence?

The formal definition of Q is the energy one, but it is no longer the common one. Q is now used as a measure of the phase angle of a two-terminal impedance, and this raises the question whether it will be possible to go back to the formal definition, or whether we should acknowledge common practice.

In Section 4.5 the loss in the valve voltmeter is simulated by a series resistance. Is the value independent of voltage, at least to the limits required by the accuracy of the instrument? If it is not, it seems doubtful whether the addition method will avoid error due to this resistance.

In Section 6, the list of points which were found important in the search for accuracy should be useful to other people designing apparatus for measuring impedance.

It is a marked advantage of this instrument that the self-inductance of the tuning condenser does not cause an error in the measurement of conductance; this inductance is often troublesome and can never be made as small as one would like.

The authors seem to have found the strays mainly by calculation, and the corrections they call for are quite important at the higher frequencies; I should like to know if there is any experimental confirmation of the calculations.

There is one stray about which I should like to make a suggestion; L_6 and R_6 come from the terminals, and are a perpetual source of trouble in measuring impedance at high frequencies, for they cannot be reduced to zero. It seems that the only way out is to agree to a standard form of terminal, so that at least the mistakes we make will all be the same. This form of terminal probably cannot always have the same physical form, for practical reasons, but we may be able to agree upon a base for our various terminals and then measure the latter as part of our unknowns. I suggest that the base could be a conducting sheet, with a hole of $\frac{1}{4}$-in or $\frac{1}{2}$-in diameter in it, and a rod at the centre of the hole. The end of the rod should be flush with the sheet, and the two would be the two terminals. Have the authors any views on this arrangement?

Mr. R. Faraday Proctor: I think that the confusion between the definitions of Q and magnification factor has arisen largely through the general neglect of the self-capacitance effect in the determination of the Q of a coil. This is particularly tempting when using a Q-meter.

When measuring the r.f. inductance and resistance of coils by the resistance-variation method, before the advent of the Q-meter, it was my general practice to correct the measurements for the self-capacitance of the coil, and to calculate the true magnification-factor, $Q = \omega L/R$, as distinct from the apparent magnification-factor, neglecting this correction.

With the introduction of the Q-meter giving a direct measurement, there has been a tendency to neglect this correction even to the extent of forgetting its existence, the apparent Q generally being sufficiently accurate.

The energy definition of Q came in, I believe, when it was desired to apply the Q-factor to cavity resonators.

Referring to Section 5, the author's design uses high-impedance injection, and might be described as the development of a design proposed by the Hazeltine Corporation of America about 14 years ago. As far as I can remember the Q-meter was first tuned to resonance and the voltage reading V noted, giving: $Q_m = \frac{V}{e}\frac{C_1 + C_2}{C_1}$ which is in agreement with the present authors.

The coil was then removed and the new voltage V_1 noted, giving $\frac{V_1}{e} = \frac{C_1}{C_1 + C_2}$; combining this with the previous equation gives $Q_m = V/V_1$

In this way the Q is obtained by two readings on the same meter, the actual values of e and C being unimportant provided they remain constant during the measurements.

In the case of high values of Q, however, this means the measurement of two widely differing voltages, a difficulty which is avoided in the authors' design. I should be glad to have further information on the derivation of the expression for L_2 in Section 4, and the approximations involved.

I am glad to see that the authors have stressed the error due to the residual parameters of the Q-meter components when the instrument is used at high frequencies, as it has been my experience that the large errors which may arise in certain cases from these causes are not fully appreciated by the general user.

Dr. L. Hartshorn: The authors have rightly pointed out that in common usage Q may mean several different quantities, but that on analysis they can all be reduced to two; these I suggest should be distinguished as magnification and selectivity, and no attempt should be made to set up one of them as "the true Q," as is done in the paper. What the Q-meter actually measures is magnification, which is primarily the voltage ratio of a tuned circuit used as a step-up transformer. The definition of this quantity necessarily depends on the input and output conditions, but the convention adopted by the authors is widely accepted, and it has the great advantage that it leads to the very useful conception of magnification as a property of any circuit element, given in terms of the basic measurable quantities by the simple relation, $Q_m = \tan\phi = X/R$. Hence there is good reason for regarding this relation as the basic definition of Q for circuit elements. The term was indeed coined to represent just this property, but it was subsequently extended to resonators in general, mechanical as well as electrical, and in a similar way the meaning of the term was also extended; for example, when we arrange resonators, say tuned circuits, tuning forks, magnetostriction resonators, cavity resonators and quartz crystals, etc., in ascending order of Q, we are not thinking of voltage magnification but sharpness of resonance or selectivity. The definition of this quantity in terms of energy ratio has the advantage that it is applicable to every type of resonator, energy being the one quantity common to all; the weakness of the definition as a basis for practical electrical measurements is that for the general circuit element, stored energy is not a measurable property, and it cannot even be inferred from the basic measurable quantities such as terminal current, voltage, and phase angle, without making some assumption about the distribution of capacitance and inductance. On

the whole, therefore, I think it would be a mistake to try to pin down Q to one master definition, the latitude commonly taken being fully justified. In many practical cases it is unnecessary to distinguish between magnification, Q_m, and selectivity, Q_s, the general symbol Q standing for whichever of the quantities is relevant to the matter in hand, the prevalent idea that Q is an abbreviation for "quality" being no less valid in the one case than the other.

The original Q-meter has an attractive simplicity of operation, and does good service in a field where high accuracy is less important than convenience and speed. The use of a standard resistor, and of a measuring circuit composed of three series-connected elements must, however, limit it to frequencies low enough to make the inductive reactance of a short length of lead negligible. The authors have tackled this limitation in the logical way; the resistor is replaced by a capacitance voltage-divider, and the series-connected circuit by a parallel-connected one. General experience confirms that measuring apparatus of this type is satisfactory at frequencies up to 150 Mc/s, and I have little doubt that the Q-meter with these features has a useful future.

Dr. V. A. Sheridan: I congratulate the authors on the method used to define Q, which, incidentally, is frequently confused with the magnification factor or the reciprocal of the power factor. I used the high-impedance injection circuit myself in 1944, and as a matter of fact, an instrument of this type was first shown in 1946 at the Physical Society's Exhibition. This was roughly three months before Dr. Biggs took out his patent. The high-impedance circuit has only one drawback when compared with the low-impedance method, and that is the difficulty in measuring the loss factor of dielectrics. As the sample under test is connected in parallel with a tuning condenser the constant ratio of C_1 and C_2 will not be maintained, hence the reading will be quite wrong. As a matter of interest, I should like to add that the latest Q-meter employs an inductive coupling between the oscillator and the test circuit and achieves the same degree of accuracy as a capacitance-feed circuit.

Mr. M. G. Scroggie: Nearly all the textbooks define Q as $\omega L/R$ for lumped circuits, and those that deal with distributed resonant circuits such as cavities usually give the energy-ratio definition too. Both seem to be covered quite satisfactorily in British Standard 204: 1943, except that the note to the effect that $1/Q$ is the power factor is not strictly in agreement. The confusion to which the authors refer arises only if $\omega L/R$ is simplified to X/R and then applied to circuit elements containing reactances of both kinds.

When the r.f. resistance of a coil is measured by a method in which the exciting e.m.f. is in series with only part of the resonant circuit, as in Fig. 3, it is universally recognized that the correction factor $C^2/(C + C_0)^2$ must be applied. Similarly the factor $C/(C + C_0)$ must be applied to the apparent inductance, $1/\omega_r^2 C$. It therefore follows that Q-meter readings must be multiplied by $(C + C_0)/C$ to give the true Q. When the coil is measured near its natural frequency this correction is large, yet the implication of the name Q-meter no doubt has often caused the correction to be overlooked, and the authors' emphasis of this point is timely.

It may be noted that the ordinary type of Q-meter can also be regarded as a capacitance-injection type in which C and C_0 are the series and shunt elements respectively. If this is done the readings will automatically be corrected to give true values of Q, etc.

In the frequency-variation method of measuring R and Q, the exciting e.m.f. is in series with the whole circuit and the correction is inapplicable to either.

In theory another correction is necessary with all Q-meter readings owing to the difference between voltage resonance and current resonance, but it is only when $Q < 7$ that this correction exceeds 1%.

It would seem to be no easy matter to ensure an accurately constant ratio over the whole working range of the capacitance potentiometer in the authors' instrument, the ratio of C_1 and C_2 being so high. Since the accuracy of readings depends directly on this ratio, it would be interesting to have more information on the actual accuracy of ganging and the means adopted for obtaining it.

Dr. M. H. Oliver: The paper describes an important advance in the design of Q-meters, and the new instrument will be a most useful addition to the equipment of radio measurements laboratories.

The authors have emphasized the great importance of the residuals L_1 and C_1, but the values they quote for these two quantities seem to be rather high. The value of L_1, for example, is given as $0{\cdot}04\ \mu$H. Is there any possibility of reducing these?

The strays associated with the measuring circuit have been calculated or measured, and from the figures it is possible to estimate the overall accuracy of the instrument at any frequency, but some experimental checks of the accuracy which is claimed would be a worthwhile addition to the paper.

There is a range of resistance values which cannot be measured on a Q-meter because the Q value obtained is too low whether the resistance is placed across the tuned circuit or in series with the coil, and the gap in the range of resistance values which can be measured decreases with increase of frequency. Can this gap be made smaller with the new Q-meter than with the low-impedance injection type?

A feature of the new instrument which the authors have mentioned is that one end of the coil is earthed, there being no 0·04-ohm resistor as in the old type. Advantage could be taken of this fact to make the measurement of low impedances in series with the coil easier and less inaccurate than with the old instrument.

It is often necessary when exploring the behaviour of an unknown impedance over a range of frequency with a Q-meter to keep the instrument in resonance as the oscillator frequency is varied. This is a long and tedious operation, particularly when the range of frequency to be covered is large, and it would be very useful to have a commercial instrument in which the tuning of the oscillator and the measuring circuit could be ganged, if necessary.

Mr. J. W. Crompton: I feel that most of the speakers in the discussion have dwelt rather on the lumped-circuit aspect of Q, and that too little has been said of Q in dealing with such high-frequency circuit elements as quarter-wave short-circuited lines. In such cases I feel that the definition of Q as the ratio of energy stored to energy dissipated per cycle, times the angular frequency, is highly to be desired, and I strongly support it.